Effectiveness and cost benefits of computer-based decision aids for equipment maintenance

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Abstract

Data were summarized from assessments of three computer-based problem solving decision aids for equipment maintenance. All three were shown to increase accuracy and reduce errors and time required to solve maintenance problems. Cost benefits were reported for one and suggested net savings of about $20 million per year in F-16 avionics maintenance. These assessments suggest that (1) a strong cost-effectiveness case can be made for these computer-based aids, (2) their development and implementation should consider the full range of options available for ensuring competent human performance, (3) both descriptive and prescriptive approaches should be employed in their design, (4) they will benefit from capabilities developed for intelligent tutoring systems, and (5) their absence from routine use despite their demonstrated promise suggests that more effort is needed to ensure that the state of practice advances along with the state of the art. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Job performance aids; Decision aids; Cost and effectiveness evaluation; Equipment maintenance; Maintenance technicians; CMAS; PEAM; IMIS

1. Introduction

Problem solving is required when an individual or a group of individuals must achieve a goal but are uncertain how to do so (Baker & Mayer, 1999; Mayer & Wittrock, 1996). It requires ingenuity and creativity on the part of the problem solvers to manipulate and transform the knowledge and skills they possess into paths of action leading to the goal. Most 'real-world' problem solving is a multivariate and complex activity steeped in uncertainty. It involves everything from household budgeting to deploying military personnel.

Decision making is an integral and inevitable component of human problem solving. It is a critical component of the skills needed to ensure workforce readiness

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and viability in the global marketplace (O'Neil, 1999). Difficulty in making the decisions needed to solve workplace problems is indicated by the frequency with which we are confronted with too much data, too many options, and unknown levels of risk. These matters have long been the object of systematic study by psychologists both past and present (James, 1890/1950; Edwards & Fasolo, 2001).

Given the complexity of real world decision-making and the range, both descriptive and prescriptive, of its theoretic underpinnings, it does not seem unreasonable to seek assistance from technology. The value of these resources is presaged by early studies of clinical and statistical predictions (Meehl, 1954). These studies were intended to show what human (clinical) judgment would add to purely statistical predictions of such outcomes as patient response to treatment or academic success. As described by Dawes (1971), the statistical prediction "floor" turned out to be a ceiling. In all 20 cases reviewed by Meehl, statistical predictions based on straight-forward linear models turned out to be superior to the clinical judgments of human beings.

Meehl's results might be taken to suggest that today we should seek to replace human decision making with computer-based algorithmic procedures that capture human processes but apply them consistently. However, this approach may go too far for at least three reasons. First, many decisions must be made in a dynamic environment. By the time the environment and the decision process can be captured within an algorithmic procedure, the need for the decision may have long passed. Second, as described by Hastie (2001), it may be impossible to capture all the elements that should be included in a decision. Elements involving intuition, social roles, identification of alternatives, payoff-probability interactions, utilities, uncertainties, etc. are often too elusive to capture in anything like an algorithmic procedure. And, third, most humans want to maintain control over their lives. They do not want their lives to be run by machines. Other reasons may well occur to the reader.

On the other hand, most people are willing to accept (even pay for) assistance and advice in making complicated decisions. The extent to which they are willing to do this depends to a significant extent on both the decision to be made and the individual(s) who must make it. Areas where a great many possibilities can be collected, stored, and accessed by computer and then organized and presented to human decision makers seem ripe for technology assistance. The value of doing so to aid human decision making, problem solving, and, generally to augment human cognition is a topic of this article. An example of such augmentation used in life or death decisions, is the clinical oncology decision aid.

1.1. Example: clinical oncology decision aid

A theoretically-based approach was used to develop the National Cancer Institute's (NCI) Clinical Trial Decision Aid (Whiteis, McGovern, & Johnston, 2001). The decision aid uses standard personal digital assistant (PDA) technology and evolving heuristics for inclusion and exclusion to assist oncologists in determining a patient's eligibility to participate in melanoma and colorectal cancer clinical trials.

Before developing this decision aid, Mozelak, Glassman, and Johnston (2001) performed a clinical oncology needs assessment with interviews, focus groups, and

surveys. They found that 14% of all cancer patients are eligible for enrollment in cancer clinical trials while only 2% are actually enrolled (National Cancer Institute Office of Communication, 2000, personal communication). Further, they found that there are hundreds of public and private clinical trials being performed nationally. New clinical trials are frequently added and existing trials are dropped with equal frequency. Each clinical trial has its own criteria for including and excluding patients, and each is subject to continuing modification by regulatory bodies and current research results. The situation makes enrollment heuristics hard to acquire and apply.

Physicians indicated that using the Internet or journals to track clinical trials in their field was an unmanageable solution that proved to be overly time-consuming and confusing because of rapid changes in trial availability. They also indicated that each trial had its own selection criteria leaving them to focus on one or two individual trials, neglect others, and seek patients who fit the criteria for the specific trials they selected. Mozelak et al. (2001) concluded that significant problems exist in enrolling cancer patients for clinical trials because of the need to manage increasing volumes of data and track the rapidly evolving inclusion and exclusion heuristics for each trial.

By searching clinical trial inclusion and exclusion criteria, Mozelak et al. determined that one could create heuristics to fit each of the clinical trials. Physicians could adjust the values of seven clinical variables, thereby reducing the number of available clinical trial choices from more than 400 to an average of three matched trials per patient. While the selection rules were not a perfect fit, they reduced the number of trials for which any patient might hypothetically qualify to a manageable number. In turn, the process increased the probability that individual patients might qualify for a clinical trial because the physician no longer needed to screen them for a limited number of trials but could identify for each patient all trials that were appropriate and applicable.

The prototype was developed on a handheld PalmOS (TM) device that downloads NCI melanoma and colorectal cancer clinical trial information each time a physician connects the handheld device to the Internet. By combining formally developed heuristics with a large source of data, the device acts as a decision aid covering many clinical trials along with their descriptions, locations, points of contact, and inclusion and exclusion criteria. The device is currently being tested against other clinical datasets to verify its inclusion and exclusion heuristics.

Recently, 80% of one sample of oncologists reported using PDA-based decision aids for this purpose (Mozelak et al., 2001). Many other applications are likely to be developed, raising issues concerning their cost and effectiveness. Their value is indicated by assessments of job-aiding devices performed by the military.

2. Military applications of technology-based decision aids

University research is primarily concerned with developing technical opportunities, not assessing cost and effectiveness trade-offs. This orientation leads to an

interest in effectiveness (Does it work?), but not necessarily to cost-effectiveness (Should anyone buy it?). Consideration of both the effectiveness and costs of a proposed innovation is essential for its transition from research laboratory to routine use (Fletcher, 1990). The primary business of business is not to advance the state of the art but to seek proprietary advantage. This situation leaves the government and particularly the military with an opportunity if not a responsibility to enhance the state of the art and practice in decision aiding through assessment of costs and effectiveness and open dissemination of findings.

Three system developments are notable in this regard. The first concerns the Computer-Based Maintenance Aids System (CMAS) developed by the Air Force Human Resources Directorate. The second concerns the Portable Electronic Aid for Maintenance (PEAM) developed together by the Army Research Institute and the Navy Personnel Research and Development Center. The third concerns the Integrated Maintenance Information System (IMIS) developed by the Human Resources Directorate in the Air Force Armstrong Laboratory.

2.1. Example: Computer-based Maintenance Aids System (CMAS)

CMAS was a logical extension of efforts to develop maintenance decision aids that could be traced at least to the 1960s with Air Force Project PIMO (Presentation of Information for Maintenance and Operation) (Serendipity, 1969). PIMO used paper-based task-specific job guides as decision aids for maintenance and was followed by other paper-based decision aids such as Xyzyx Corporation's Job Performance Aids on cards (Inaba, 1988).

Paper-based decision aids were shown to be better than conventional technical manuals in improving technician performance (e.g. Booher, 1978; Foley & Camm, 1972), but they shared and continue to share the usual drawbacks of paper-based technical manuals in that they are expensive and inefficient to update, it is difficult to design their presentations to match the differing needs of novice, journeymen, and experienced technicians, they often make access to information difficult to find, and they are heavy and cumbersome to store and use.

Computer technology early entered the scene with recipe conversion aids presented by the PLATO (Programmed Logic for Automatic Teaching Operations) instructional system. Hurlock and Slough (1976) reported that the capability was effective, but, given the state of computer technology at the time, too expensive and too cumbersome for routine use. In 1977, this capability was extended by the Air Force Computer-Based Maintenance Aid System (CMAS) project (Clay, 1986). CMAS began the development of concepts for presenting maintenance aiding information by computer and initiated a chain of developmental efforts continuing into today's Interactive Electronic Technical Manuals (IETMs) and the 'mentoring' (decision aiding) capabilities now incorporated in the Advanced Distributed Learning Initiative.

Nugent, Sander, Johnson, and Smillie (1987) compared the troubleshooting performance of 36 technicians using technical manuals with technicians using electronic presentation of an augmented CMAS data base to detect and isolate single

component failures in a radio receiver-transmitter. Four problems were presented, two to be solved using decision aiding presented by technical manuals and two to be solved using the electronically presented decision aiding. Nugent et al. found that technicians using CMAS compared to those using paper-based technical manuals took less than half the time to find system faults (average of 24.4 min versus 56.5 min), checked more test points (average of 5.6 versus 3.6), made no false replacements (versus an average of 1.2), and solved more problems (average of 2.0 versus 1.7). All their results were statistically significant.

2.2. Example: Portable Electronic Aid for Maintenance (PEAM)

PEAM followed DARPA (Defense Advanced Research Projects Agency) development in the late 1970s of VIMAD (Voice Interactive Maintenance Aiding Device), which was the first voice-controlled, wearable computer intended as a maintenance decision aid. PEAM also was portable (briefcase-size) and used voice interaction to allow hands-free access to textual and graphics maintenance information needed by technicians. For a variety of reasons, the evaluations reported here did not use voice interaction to any significant extent.

Evaluation of PEAM was a joint Service effort summarized by Wisher and Kincaid (1989). It involved both Army and Navy technicians. The Army used PEAM and, alternatively, a lap-top computer to provide PEAM-based maintenance decision aiding for M1 tank turrets. The Army used a between-subjects evaluation with nine technicians assigned to the PEAM group and five technicians assigned to a paper-based technical manual group. Both groups of technicians solved six troubleshooting tasks and 28 non-troubleshooting tasks—three adjust and align tasks, two service maintenance tasks, 11 unit removal tasks, and 12 install/replace tasks.

The Navy presented PEAM material using a workstation-size computer to provide PEAM-based maintenance decision aiding for the NATO SEASPARROW missile. It used a within-subjects design with 28 technicians required to solve two fault isolation (troubleshooting only) problems, one using technical manuals, and one using PEAM simulation.

Wisher and Kincaid report substantial reductions in troubleshooting errors for both the Army (average of 0.7 versus 3.4 errors) and Navy (average of 0.9 versus 5.7 errors) technicians for the PEAM applications. The Army study also observed and reported reductions in errors among the PEAM technicians solving non-troubleshooting problems (average of 0.4 versus 1.1 errors). All these differences are of statistical significance as well as of practical significance in military operations.

Results concerning time to perform tasks were mixed, probably due, as Wisher and Kincaid suggest, to the long time (in excess of 15 s) it took for graphics to appear on the Army PEAM systems. As a consequence the Army technicians using PEAM took longer to perform both troubleshooting (average of 41.6 versus 37.0 min) and non-troubleshooting (average of 16.1 versus 12.0 min) tasks, although neither of these differences was statistically significant. On the other hand, using a more powerful computer for PEAM permitted the Navy technicians to finish their

troubleshooting tasks more quickly (average of 33.1 versus 43.9 min). This difference is statistically significant.

2.3. Example: Integrated Maintenance Information System (IMIS)

Perhaps the best and most complete evidence on the value of technology-based decision aiding is provided by assessments of the Integrated Maintenance Information (IMIS). Tomasetti et al. (1993) documented a thorough cost analysis of IMIS, Thomas later (1995) reported results from an empirical investigation of IMIS effectiveness, and Teitelbaum and Orlansky (1996) summarized results from both these studies, combined them into a more complete cost-effectiveness assessment, and discussed the implications of these findings.

Thomas (1995) compared the performance of 12 Avionics Specialists and 12 Airplane General (APG) Technicians on 12 fault isolation problems concerning three F-16 avionics subsystems—the fire control radar, heads-up display, and inertial navigation system. Within each of the two groups of subjects, six of the fault isolation problems were performed using paper-based Task Orders (Air Force technical manuals) and six were performed using IMIS. Training for APG Technicians includes all aspects of aircraft maintenance, only a small portion of which concerns avionics. In contrast, Avionics Specialists must meet higher selection standards and receive specialized training focused on avionics maintenance.

Results from these investigations may be summarized as the following:

(a) Avionics Specialists using Task Orders compared with those using IMIS. The Avionics Specialists using IMIS found more correct solutions (100% versus an average of 81.9%) in less time (average of 123.6 versus 149.3 min), used fewer parts (average of 6.4 versus 8.7) to do so, and took less time (average of 1.2 versus 19.4 min) to order them. All these results were statistically significant.

The number of parts required and the time to order them may deserve brief comment. Savings in spare parts inventory and transportation were by far the largest factors in the Tomasetti et al. (1993) costs–benefits analysis. They exerted considerable leverage on the overall cost savings reported by Teitelbaum and Orlansky (1996) for IMIS. The results concerning time to order parts are to be expected because IMIS automates most of this process. These results are mentioned here because they are large and because the time taken by technicians to complete the paperwork in the absence of IMIS could be used elsewhere, with substantial productivity gains and cost savings, if IMIS were performing these paperwork chores.

(b) APG Technicians using Task Orders compared with those using IMIS. Thomas obtained similar results in these comparisons. The APG Technicians using IMIS found more correct solutions (98.6% versus 69.4%) in less time (average of 124.0 versus 175.8 min), used fewer parts (average of 5.3 versus 8.3) to do so, and took less time (average of 1.5 versus 25.3 min) to order them. As with the Avionics Specialists, all these results were statistically significant.

(c) APG Technicians using IMIS compared with Avionics Specialists using Task Orders. The APG Technicians using IMIS found more correct solutions (98.6% versus 81.9%) in less time (average of 124.0 versus 149.3 min), used fewer parts to

do so (5.3 versus 8.7), and took less time (1.5 versus 19.4 min) to order them than did Avionics Specialists using paper-based Task Orders. All these results were statistically significant. This result suggests that it is feasible, and desirable to replace some of the extra training required by specialists with on-the-job, just-in-time decision aids, such as IMIS, supplied to non-specialists.

(d) APG Technicians using IMIS compared with Avionics Specialists using IMIS. In these comparisons, the APG Technicians performed just about as well as the Avionics specialists (98.6% versus 100%), and even slightly better in the number of parts used (5.3 versus 6.4). None of these comparisons were statistically significant and none appear to be practically significant. These results again suggest the feasibility of replacing some number of specialists with their greater training costs and requirements with general technicians provided with on-the-job, just-in-time decision aids. They also suggest the desirability of doing so, because in this case the training costs of the specialists are greater than those of the non-specialists even though the resulting performance on the job, where it counts, is the same in both cases.

The promise suggested by these results could well vanish if the costs to provide the decision aid (IMIS) exceed the costs they otherwise save. Enter the costs and benefits analysis by Tomasetti et al. (1993) combined with the empirical results reported by Thomas (1995). By using these two sources of data, Teitelbaum and Orlansky (1996) were able to estimate reductions in depot-level maintenance, organizational-level maintenance, and maintenance and transportation of inventories of spare parts. They arrived at an estimated annual savings from the use of IMIS of about $38 million for the full Air Force fleet of about 1700 F-16s. Teitelbaum and Orlansky also considered the costs to develop and maintain IMIS. Assuming an 8-year useful life for IMIS, they arrived at a figure of about $18 million per year to maintain IMIS (including its databases) and to amortize its development costs. The result is a benefit of about $20 million per year in net savings.

This figure of $20 million is conservative. It does not include such aspects as: (a) savings in selection and training that would result from a reduction in Air Force requirements to recruit and train specialized personnel such as the Avionics Specialists in Thomas' study; (b) savings in training that would accrue from the use of IMIS as both a decision aid and a training device; (c) savings in the costs to print, distribute, and, especially, update paper technical manuals; and (d) savings (of about 50%) in time to debrief pilots about maintenance problems. Most importantly these benefits do not include those arising from increased sortie rates and unit operational readiness and effectiveness resulting from the substantially improved problem solving competencies of maintenance personnel.

3. Discussion and conclusions

At least six observations may be made concerning the findings reported above. First, the Oncology Aid, CMAS, PEAM, and IMIS are all aids in decision-making and problem solving. Capabilities such as job performance aids, electronic

performance support systems, technology-based 'mentoring', as well as those more typically described as individual and group decision aids are all intended to match user intentions and relevant data with decision heuristics that can advise users across a full range of problem solving. Along with many other things, this range includes the maintenance of devices and systems. Decision aiding in maintenance has yielded useful evidence on effectiveness and cost returns that indicate the general value of technology-based problem solving.

Second, the results discussed in this paper suggest that a strong cost-effectiveness case might be made for the development and implementation of technology-based decision aids across a variety of applications. More data of this sort would be needed for a conclusive case, but, as current findings suggest, so far, so good. What is not clearly evident is how these technology-based capabilities should be best designed. Current functional designs are based on best guesses. We have much yet to learn about what functionalities should be included to insure that these technology-based capabilities to serve as effective partners in human decision making and problem solving. To accomplish this end we need to know more about both the functionalities we are able create and the human problem solving processes we mean to assist.

Third, a decision, for instance, to supply IMIS to all Air Force APG technicians may be a good idea, but it should not be extended to wholesale replacement of all avionics specialists and avionics specialist training with IMIS. It should be undertaken with full consideration of all other components of Air Force efforts to ensure the provision of human performance when and where it is needed.

More generally, aids for decision aiding and problem solving need to be treated as components of a system intended to ensure the availability of human competence. The object is not just effective decisions or problem solving alone, but an effective organization. Resources to accomplish this end can be allocated to selection standards for people who are to solve the problems, structuring the tasks, jobs, and careers to which they are assigned, training and education provided for them, and, of course, the design and implementation of the decision aids they will use. All these components interact. An investment (or lack thereof) in one affects all the others, as well as the functioning of the organization as a whole. Determining these allocations should be treated as part of the full system of human competence needed by the organizational entity, be it a company, university, or governmental agency, i.e. regardless of the economic sector in which it acts.

Fourth, as Edwards and Fasolo (2001) discuss, there are necessary roles for both descriptive and prescriptive approaches in the design of decision aids. Prescriptive theories help by explaining, often in quite formal terms that are amenable to algorithmic procedures, how decisions should be made based on well-defined criteria and optimized consideration of alternatives. Techniques like von Neumann and Morgenstern's (1947) utility theory, Simon's (1955) rational choice theory, and Kahneman and Tversky's (1979) prospect theory are all applicable. Edwards and Fasolo assembled current prescriptive techniques under three widely-used, general approaches derived from multi-attribute utility measurement, Bayesian probability rules, and maximization of subjectively expected utility, all of which can play a role in good decision making.

Descriptive approaches, on the other hand, attempt to explain how people actually make decisions in 'real life.' These approaches often use case studies to understand and explain decisions by explaining the actors, context of the decisions, and intended outcomes in these cases. Examples of this second category include Allison's (1971) analysis of decision making in the Cuban missile crises and Wohlstetter's (1962) analysis of the surprise attack at Pearl Harbor. Such descriptive approaches were used extensively in the design of the Oncology Aid.

An interesting synthesis of descriptive and prescriptive approaches is provided by naturalistic decision-making (NDM) (e.g. Orasanu and Connolly, 1993; Klein, 2000). NDM combines elements of formal models with reason-based analysis, elicitation, and direct observation. Zsambok (1997) describes NDM as "[T]he way people use their expertise to make decisions in field settings" (p. 4). It attempts to capture and describe decision making by observing and interviewing individuals (as in descriptive approaches) and abstracting from these cases more formal models (as in prescriptive approaches), such as Klein's Recognition-Primed Decision Model (Klein, Calderwood, & Clinton-Cirocco, 1985) which categorizes decision-making stages and strategies. A systematic effort to apply NDM to the maintenance aiding applications discussed in this paper, may be an important next step in their development.

Fifth, if we seek technologies that will participate as partners in human problem solving, these technologies may need to understand the human side of the issue. To some extent they may need to be 'intelligent'. For instance, the primary need for maintenance technicians (and other problem solvers) is not a capability that starts at the beginning of a procedure and leads them through to the end—valuable as this may be. More typically, maintenance technicians begin troubleshooting or a specific procedure, encounter anomalies, and need help. In short they more typically need help when they are 'stuck' in the middle of a procedure. What would help is a device with the capability to engage in an decision aiding, mixed dialogue with either the technician or the decision aid taking the initiative to ask questions, seek clarification, access data bases, and suggest measurements and hypotheses. Much is made of dialogue management in tutorial instruction (e.g. Graesser, Person, & Magliano, 1995). A capability for dialogue management in problem solving in general and maintenance aiding in specific is needed and should be developed. This suggests a collaboration between decision aiding communities and the intelligent tutoring communities. Both communities should rise to the occasion.

Other 'intelligence' is required in technology-based problem solving and decision aiding. As described by Fletcher (2002), among many others, this intelligence is needed for comprehensive coverage of the decision space so that the actions suggested are relevant and applicable. Intelligence is also needed to represent the user, so that advice is given in a form that the user—at whatever level of knowledge, intent, or ability—is capable of understanding and using. Finally, heuristics are needed to infer solutions to the problem presented. These capabilities are to one degree or another present in intelligent tutoring systems and decision aids. It is not a great distance from Sherlock's demonstrated intelligent avionics training capabilities (Gott, Kane, & Lesgold, 1995) to avionics decision aiding. Again, the communities

concerned with these developments would benefit from increased coordination and communication.

Sixth, in contrast to the favorable findings reported in this paper, and the promise of even more capabilities as technology-based decision aids are developed, it is notable that only one of the devices, the Oncology Decision Aid, is currently in use. CMAS, PEAM, and IMIS, as well as Sherlock, are all absent from daily practice. The research and development community has assumed the responsibility to advance the state of the art, and has been successful in fulfilling it. The complementary responsibility to advance the state of practice in decision aiding and problem solving through technology transfer and engineering in the field does not appear to be receiving the attention it needs.

4. Final word

This brief summary presages an evolving and perhaps inevitable future in which hand-held, or more likely wearable, personal technology-based learning and problem-solving assistants will be as common as wristwatches. They will be widely used to augment human cognition and enhance human competency. In Norman's (1993) terms and as evidenced by the findings reported in the paper, we can build tools that make us 'smart'. We will communicate with them in natural language and they, in turn, will communicate with the global grid to provide advice and information. How well they articulate this advice and information back to the individuals using them will depend to some extent on how well they understand each individual's needs, intentions, and capabilities. As suggested here and elsewhere, capabilities for individualizing presentations and communications are evolving in a number of domains such as human computer interaction, modeling and simulation, and intelligent tutoring (Fletcher, 2002).

But how well they enhance human problem solving will also depend on how well those who design and build these devices understand the processes we use to solve problems. What is the optimal, the most effective division of labor between humans and machines? Meehl's (1954) ancient finding still stands—procedures that capture our decision processes, but avoid human distractions and foibles, make better decisions, at least in some domains, than we do. Results presented in this paper suggest that we can indeed use technology to make us smart. Having learned *that* this is possible, we now need to learn *how* it is best done. We need to progress from art to engineering. As shown by other papers in this special issue, we are developing the understanding we need. The results presented here suggest that efforts to do so will be worthwhile.

References

Allison, G. (1971). *Essence of decision. Explaining the Cuban missile crises.* Boston, MA: Little, Brown and Company.

Baker, E. L., & Mayer, R. E. (1999). Computer-based assessment of problem solving. *Computers in Human Behavior*, *15*, 269–282.

Booher, H. R. (1978). *Job performance aids: research and technology state of the art (TR 78–26)*. San Diego, CA: Navy Personnel Research and Development Center (DTIC/NTIS ADA 057 562).

Clay, J. D. (1986). *Development of computer-based maintenance aid system*. Wright-Patterson Air Force Base, OH: Air Force Human Resources Laboratory.

Dawes, R. M. (1971). A case study of graduate admissions: application of three principles of human decision making. *American Psychologist*, *26*, 180–188.

Edwards, W., & Fasolo, B. (2001). Decision technology. In S. T. Fiske, D. L. Schacter, & C. Zahn-Waxler (Eds.), *Annual review of psychology, vol. 52* (pp. 581–606). Palo Alto, CA: Annual Reviews.

Fletcher, J. D. (1990). Computer based instruction: costs and effectiveness. In A. P. Sage (Ed.), *Concise encyclopedia of information processing in systems and organizations*. Oxford, England: Pergamon Press.

Fletcher, J. D. (2002). What do sharable instructional objects have to do with intelligent tutoring systems, and vice versa? *International Journal of Cognitive Ergonomics*, *5*, 317–333.

Foley, J. P., & Camm, W. B. (1972). *Job performance aids research summary*. Wright-Patterson Air Force Base, OH: Air Force Human Resources Laboratory (DTIC/NTIS ADA 697 034).

Gott, S. P., Kane, R. S., & Lesgold, A. (1995). *Tutoring for transfer of technical competence (AL/HR-TP-1995–0002)*. Brooks AFB, TX: Armstrong Laboratory, Human Resources Directorate.

Graesser, A. C., Person, N. K., & Magliano, J. P. (1995). Collaborative dialogue patterns in naturalistic one-to-one tutoring. *Applied Cognitive Psychology*, *9*, 1–28.

Hastie, R. (2001). Problems for judgment and decision making. In S. T. Fiske, D. L. Schacter, & C. Zahn-Waxler (Eds.), *Annual review of psychology, vol. 52* (pp. 653–683). Palo Alto, CA: Annual Reviews.

Hurlock, R. E., & Slough, D. A. (1976). *Experimental evaluation of PLATO IV technology: final report (NPRDC TR 76Q-44)*. San Diego, CA: Navy Personnel Research and Development Center.

Inaba, K. (1988). *Some lessons learned from PEAM*. Canoga Park, CA: XYZYX Information Corporation.

James, W. (1890/1950). *Principles of psychology: vol. I*. New York: Dover Publications.

Kahneman, D., & Tversky, A. (1979). Prospect theory: an analysis of decision under risk. *Econometrica*, *47*, 263–291.

Klein, G. (2000). How can we train pilots to make better decisions? In H. F. O'Neil, & D. Andrews (Eds.), *Aircrew training and assessment: methods, technologies, and assessment* (pp. 165–195). Mahwah, NJ: Lawrence Erlbaum Associates.

Klein, G., Calderwood, R., & Clinton-Cirocco, A. (1985). *Rapid decision making on the fire ground (KA-TR-84–41–7)*. Yellow Springs, OH: Klein Associates (Prepared under contract MDA903–85-G-0099 for the US Army Research Institute, Alexandria, VA) (DTIC/NTIS ADA 199 492).

Mayer, R. E., & Wittrock, M. C. (1996). Problem solving transfer. In D. C. Berliner, & R. C. Calfee (Eds.), *Handbook of educational psychology* (pp. 47–62). New York: Macmillan.

Meehl, P. E. (1954). *Clinical versus statistical prediction: a theoretical analysis and review of the literature*. Minneapolis, MN: University of Minnesota Press.

Mozelak, B., Glassman, B., & Johnston, R. (2001). Personal digital assistant uses and preferences among clinical oncologists: a needs assessment. In *Proceedings of the Fourteenth IEEE Symposium on Computer-Based Medical Systems* (pp. 529–534). Bethesda, MD: National Library of Medicine.

Norman, D. A. (1993). *Things that make us smart*. Cambridge, MA: Perseus Books.

Nugent, W. A., Sander, S. I., Johnson, D. M., & Smillie, R. J. (1987). *Troubleshooting performance using paper and electronic documentation (NPRDC TN 87–41)*. San Diego, CA: Navy Personnel Research and Development Center (DTIC/NTIS ADA 185 256).

O'Neil, H. F. Jr. (1999). Perspectives on computer-based performance assessment of problem solving. *Computers in Human Behavior*, *15*, 255–268.

Orasanu, J., & Connolly, T. (1993). The reinvention of decision making. In G. Klein, J. Orasanu, R. Calderwood, & C. Zsambok (Eds.), *Decision making in action: models and methods* (pp. 3–20). Norwood, NJ: Ablex.

Serendipity, Inc. (1969). *Project PIMO final report: PIMO final report summary vol. 1 (TR-69–155)*.

Norton Air Force Base, CA: Air Force Systems Command, Space and Missile Systems Organization (DTIC/NTIC AD 852 101).

Simon, H. (1955). A behavioral model of rational choice. *Quarterly Journal of Economics*, *69*, 99–118.

Teitelbaum, D., & Orlansky, J. (1996). *Costs and benefits of the integrated maintenance information system (IMIS) (IDA Paper P-3173)*. Alexandria, VA: Institute for Defense Analyses (DTIC/NTIS ADA 312 884).

Thomas, D. L. (1995). *Integrated maintenance information system: user field demonstration and test executive summary (AL/HR-TR-1995–0033)*. Wright-Patterson Air Force Base, OH: Human Resources Directorate, Logistics Research Division (DTIC/NTIS ADA 293 250).

Tomasetti, R. J., Calogero, A. R., Jones, C. E., Hanna, C. L., Guarino, T. J., Dimpsey, L. E., White, M. A., Cammisa, M. X., Hodak, K. K., Lloyd, B. A., & Burright, B. K. (1993). *Initial estimates of integrated maintenance information system (IMIS) costs and benefits vol. I: main report (AL/HR-TR-1993–0178)*. Wright-Patterson Air Force Base, OH: Human Resources Directorate, Logistics Research Division (DTIC/NTIS ADA 276 144).

von Neumann, J., & Morgenstern, O. (1947). *Theory of games and economic behavior*. Princeton, NJ: Princeton University Press.

Whiteis, D., McGovern, K., & Johnston, R. (2001). *NCIcon*. Patent Pending.

Wisher, R. A., & Kincaid, J. P. (1989). *Personal electronic aid for maintenance: final summary report (ARI-RR-1516)*. Alexandria, VA: US Army Research Institute (DTIC/NTIS ADA 210 348).

Wohlstetter, R. (1962). *Pearl Harbor: warning and decision*. Stanford, CA: Stanford University Press.

Zsambok, C. (1997). Naturalistic decision making: where are we now? In C. Zsambok, & G. Klein (Eds.), *Naturalistic decision making* (pp. 3–16). Mahwah, NJ: Lawrence Erlbaum Associates.